No Free Lunch: Analyzing the Cost of Deep Decarbonizing Residential Heating Systems

Anupama Sitaraman, Noman Bashir, David Irwin, Prashant Shenoy
University of Massachusetts Amherst
asitaraman@umass.edu, nbashir@mit.edu, deirwin@umass.edu, shenoy@cs.umass.edu

***Abstract*—Recent studies have analyzed the carbon footprint of residential heating and proposed transitioning to electric heat pumps as an important step towards decarbonization. Electric heat pumps are more energy-efficient than gas furnaces and use electric grid power, which is generally less carbon-intensive than directly burning fossil fuels. The transition to electric heat pumps only solves half of the problem. Electric grids, in most parts of the world, are primarily powered by carbon-intensive fossil fuels and may never be completely carbon-free. Furthermore, the added electricity demand of heat pumps may trigger expensive upgrades in the electric grid. A deep decarbonization of residential heating can be achieved by using co-located solar photovoltaic (PV) systems with battery storage alongside heat pump retrofits. However, there is no free lunch and a deeper decarbonization comes at a significant cost. In this paper, we use data from 4,413 real-world homes to analyze the additional electricity demand due to heat pumps. We investigate the problem of sizing solar panels and storage to completely offset the added demand and investigate the tradeoff between cost and carbon emission reduction benefits. Our analysis suggests that co-located solar PV systems are an effective and carbon-free alternative to the power grid, and can reduce carbon emissions by at least 58%.**

***Index Terms*—decarbonization, residential heating, solar PV and storage, air-source electric heat pumps.**

I. Introduction

Residential heating constitutes a significant portion of the annual energy bill for households in many parts of the world that experience colder climates [1], [2]. Fossil fuels, namely natural gas, propane, and oil, account for 64% of the global energy used for residential heating, resulting in the generation of 2,500 Mt of carbon emissions per year in the United States alone [3]. The impact of climate change is leading to extremely low temperatures during winter [4], which is expected to significantly increase the annual heating energy demand and costs in various parts of the world. For example, the heating costs for Massachusetts residents are expected to increase by 28% on annual basis [5]. Given these factors, the decarbonization of residential heating by adopting cleaner technologies like air-source heat pumps plays a vital role in the energy transition toward a low-carbon future.

Air-source heat pumps (ASHPs) utilize efficient heat exchange technologies to deliver more effective residential heating compared to traditional fossil fuel-based furnaces. Electrifying residential heating through electric heat pumps offers substantial reductions in carbon emissions, and additional progress can be made as the electric grid transitions to cleaner energy sources [6]. However, previous studies primarily focused on the decarbonization benefits when comparing heat pumps to natural gas and other fossil fuels for residential heating. While transitioning to electric heat pump-based heating immediately reduces carbon emissions, it does not eliminate them entirely, and thus fails to fully address the issue. Notably, the carbon emissions of an electric heat pump depend on the carbon intensity of the grid's energy supply. As the grid still relies on fossil fuel-based generation sources for a portion of its demand, electrifying residential heating will not entirely eliminate carbon emissions.

The efficiency of electric heat pumps is measured using Coefficient of Performance (COP) or using the Heating Seasonal Performance Factor (HSPF), both of which are influenced by the ambient temperature. As the ambient temperature decreases, the energy efficiency of even the state-of-the-art electric heat pumps decreases significantly. However, previous studies estimating the electricity demand from transitioning gas-based heating have made a simplistic assumption of a constant COP value throughout the year [6], [7]. This approach underestimates the overall electricity demand for residential heating and the peak electric demand on the grid that typically occurs during extremely cold weather when the ambient temperature is exceptionally low. Consequently, prior research may only provide a conservative underestimate of the impact of the residential electric heating demand on the electric grid.

In order to gain a more accurate view of the residential electric heating demand, we generate three models of COP, and analyze the impact of these models. The three models that we consider are (i) a maximum theoretical efficiency model, (ii) a static model used by the prior work [6], [7], and (iii) a dynamic model that considers the effect of ambient temperature.

Using electric heat pumps is not enough to fully decarbonize a residential area, as electric heat pumps used in homes will draw from the grid, which may be fueled by nonrenewable sources. To maximize the decarbonization benefits of electrifying residential heating, we examine the viability of utilizing on-site renewable energy sources, such as rooftop solar photovoltaic (PV) panels, in conjunction with local energy storage, to supply clean energy to installed electric heat pumps.

However, given the substantial energy consumption of even efficient electric heat pumps, the cost of implementing on-site renewable energy must be carefully weighed against its potential carbon reduction benefits. Moreover, as renewable energy sources are intermittent and solar energy is unavailable at night, the inclusion of energy storage becomes necessary, albeit at an increased cost. Given this, our research focuses on

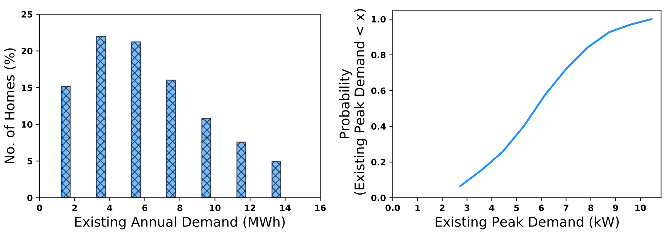


Fig. 1. ***(a) Probability distribution of grid's existing annual electricity demand (left) and (b) existing peak electricity demand (right).***

a comprehensive sizing analysis of on-site solar systems and energy storage, aiming to pursue a robust decarbonization approach that integrates electric heat pumps with local renewable energy sources and storage.

In doing our analysis, we make the following contributions:

Electricity demand analysis: We examine the impact of transitioning to electric heat pumps by analyzing real-world data from 4,413 homes from a northeastern city in the United States. Our comprehensive analysis includes evaluating the annual additional electricity demand, peak additional electricity demand, and aggregate peak electricity demand with and without the additional heat pump demand. To accurately convert gas-based heating demand to electricity demand, we utilize realistic models for the COP of electric heat pumps that consider the ambient temperature.

Deep decarbonization analysis: We further analyze deep decarbonization through the integration of solar PV systems with battery storage. We explore various approaches for sizing solar PV plus battery storage systems and assess their cost and effectiveness in reducing the additional electric heating demand on the electric grid and ultimately carbon emissions.

Cost and emissions analysis: We compare the cost of deep decarbonization using solar plus storage to achieve different levels of carbon emission reductions. Our findings indicate a 58% reduction in emissions at a low cost of $1360, but an additional 3.58× investment is required to mitigate the remaining 42% of carbon emissions from residential heating.

II. Background

In this section, we present background on decarbonizing heating, electric heat pumps, and solar photovoltaic.

Decarbonizing heating. Home heating accounted for 32% of the household energy usage and 34.5% of the residential sector carbon emissions in 2021 [5]. Fossil fuels, such as natural gas, distillate fuel oil, and propane fulfilled 63.6% of this energy usage and contributed to most of the carbon emissions from heating [5]. Prior work has proposed transitioning gas-based heating to electric heat pumps as an important step towards decarbonizing the residential sector [8]–[13]. The benefits of this transition are twofold: first, electric heat pumps are more energy efficient than gas furnaces and thus will reduce the overall energy consumption of heating; second, carbon-intensity[1] of the electric grid is significantly less than burning fossil fuels in household furnaces. While transitioning to heat pumps significantly reduces the carbon footprint of heating, it does not completely eliminate carbon emissions. The US electric grid has a carbon intensity of 393 gCO_2eq/kWh, which is expected to drop to 232 gCO_2eq/kWh by 2050 [5]. This means that transitioning to electric heat pumps powered by the electric grid solves only part of the problem and is not sufficient to fully decarbonize heating.

[1]the amount of carbon dioxide released per unit of energy consumed.

Electric heat pumps. Electric heat pumps are an alternative to fossil fuel-based heating during the winter and home cooling during the summer. Electric heat pumps are highly energy-efficient as they warm or cool a home by transferring heat from or to the outside air, as opposed to the fuel combustion used by furnaces. Homes can achieve up to 60% reduction in their heating costs by transitioning to energy-efficient electric heat pumps. In the past, a key bottleneck to wide-scale adoption has been the degraded heating capacity of the old heat pumps at low temperatures, which necessitated a backup heat source. The most common types of electric heat pumps are ducted air-source heat pumps [14]. These new and energy-efficient electric heat pumps work well even in extremely cold environments, which has led to higher adoption. However, the energy efficiency of heat pumps depends on the ambient temperature; it decreases as the temperature decreases. We use a model that determines the coefficient of performance of the electric heat pumps based on the ambient temperature [15].

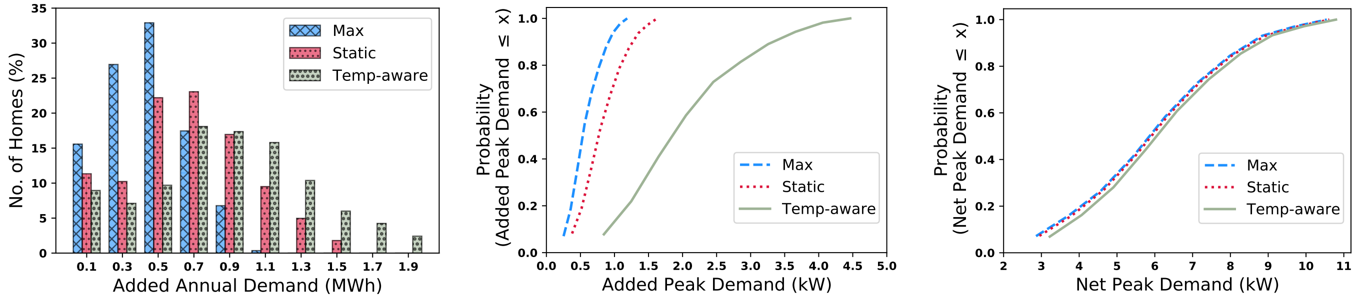
Solar photovoltaic. Solar photovoltaic (PV) accounts for 82% of the renewable energy consumption in the residential sector and 12.7% of electric power generation from renewable resources in the United States [5]. The large-scale adoption of solar PV is fueled by its declining cost, zero operational carbon footprint, and modular nature that allows installations of a few watts to many megawatts. In addition, federal and state governments offer generous subsidies to solar PV adopters that can amount to more than 50% of the total system cost depending on the installation size [16]. In addition, the cost of battery storage dropped by 72% from 2015 to 2019 and the trend is expected to continue [17]. As a result, solar PV is an ideal candidate for deep decarbonization of household heating for the single family homes that we consider in our analysis.

III. Impact on Electric Grid

In this section, we present our data analysis setup and an analysis of the impact of electric heat pumps on the electric grid. The goal for the analysis is to answer the following question: How much additional demand, annual and peak, is added to the grid as a result of heat pump retrofits?

A. Data Analysis Setup

Our subsequent analysis utilizes gas and electricity demand data collected at an hourly granularity from a city in the northeast region of the United States. Since our gas demand data includes all gas end uses, such as gas stoves, heating, and water heating, we need to isolate the heating component of the demand. To achieve this, we subtract the average summer gas demand from the overall gas usage throughout the year. This assumption is based on an insight that there is no heating



(a) Added Annual Demand (b) Added Peak Demand (c) Net Peak Demand

Fig. 2. ***(a) Probability distribution of added annual electricity demand. (b) Cumulative distribution of added peak electricity demand and (c) net peak electricity demand after transitioning gas-based heating to electric heat pumps.***

demand during the summer. Any gas consumption during the summer is solely for non-heating purposes and remains constant throughout the year.

To estimate the net gas demand for heating, we assume an 87.5% efficiency for the gas furnace to compute the energy demand for gas-based heating. The electricity demand of heating depends on the Coefficient of Performance (COP) for the electric heat pumps, which depends on the ambient temperature and the set point temperature inside the building. To demonstrate the effect of COP on electricity demand, we employ three different models that represent: (i) theoretical maximum efficiency (COP_{max}), (ii) constant COP used in prior work [6], [7] (COP_{static}), and (iii) a realistic temperature-dependent COP model (COP_{temp}).

The COP_{max} model is mathematically characterized as,

$$COP_{max} = T_{cold}/(T_{hot} - T_{cold}). \quad (1)$$

Here, T_{cold} is the temperature of the cold side and T_{hot} is the temperature of the hot side. We set the set point temperature of the building to 70°F. Here, T_{hot} is computed as $max(T_{indoor}, T_{outdoor})$. where, T_{indoor} and $T_{outdoor}$ are indoor and ambient temperature for the building respectively. Given this, T_{cold} is computed as $min(T_{indoor}, T_{outdoor})$.

Our second model is COP_{static}, which has been commonly used by the prior work [6], [7] to estimate electricity demand from the heating. This model assumes that the efficiency of the heat pumps does not depend on the temperature and remains constant throughout the year. Our static model based on the formula [18] written as,

$$COP_{static} = 0.293 \times HSPF. \quad (2)$$

Here, HSPF is the Heating Seasonal Performance Factor that specifies the amount of heat generated in British Thermal Units (BTUs) per kilowatt-hour (kWh) of energy. HSPF also varies among different climates. Given this, we based our model on the Mitsubishi Mini-Split Heat Pumps [15] datasheet which has an HSPF of 10.6 in the location it was tested in. This HSPF value corresponds to 10,100 BTUs per kWh. We get a static COP of 3.1 based on the model in Eq. 2.

Finally, to more accurately estimate COP, we employ a model that considers the impact of ambient temperature on COP of electric heat pumps, which we refer to as COP_{temp}. We generated this model from experimental data on Mitsubishi Mini-Split Heat Pumps [15].The model was generated by creating a least-squares regression line based on 7 COP values of single heat pump at various temperatures This *temperature-aware* COP is computed as,

$$COP_{temp} = 0.015 \times T_{outdoor} + 1.91. \quad (3)$$

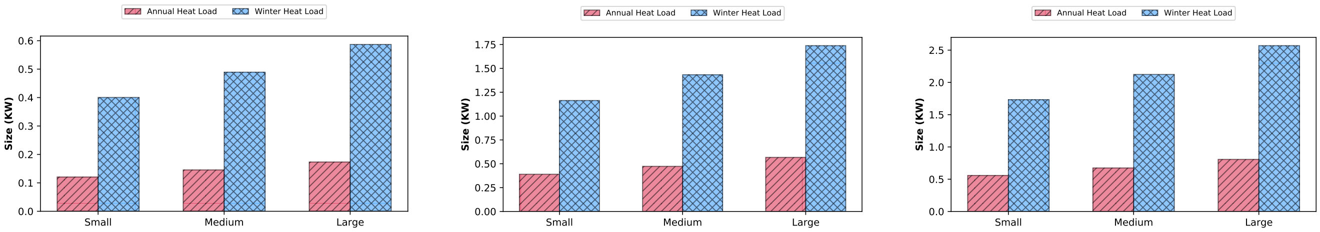
Here, $T_{outdoor}$ is measured in Fahrenheit (°F). This model assumes the set point temperature of the building to be 70°F.

To calculate the total carbon footprint of electric heating, we use a carbon emission factor of 0.000386 MT CO_2/kWh for electricity [19], which represents the average carbon intensity value for the electric grid in the United States in 2022. Additionally, as part of this analysis, we remove outlier data by eliminating the upper and lower 5% of calculated data points.

B. Electric Heating Demand Analysis

In this section, we examine the impact of transitioning to electric heat pumps on the demand of the electric grid. Previous studies have primarily analyzed the additional annual electricity demand resulting from this transition [6], which is useful for long-term capacity planning of the electric grid. However, in the short term, the increase in peak electricity demand becomes more significant as it may necessitate upgrades to transformers, power cables, and other components of the grid. Therefore, our analysis extends beyond the annual demand and incorporates the examination of peak demand generated by heat pumps. Additionally, we investigate how the electric heating demand affects the net-peak demand of the grid under the three aforementioned models of COP for electric heat pumps. This comprehensive approach allows us to understand both the long-term and short-term implications of electric heat pump adoption on the electric grid. In conducting this analysis, we answer the following questions.

(1) ***What is the existing electric demand on the grid?*** We first look at the existing electric grid demand as it provides context for the additional electricity demand from electric heat pumps. We look at the annual electricity demand and the peak electricity demand for all the homes in our analysis. Figure 1a shows the existing annual demand on the electric grid with an average of 7.79 MWh across all the homes. The maximum annual demand across all the homes is 13.94 MWh. We observe that the average annual electricity demand for homes in our dataset is less than the national average



(a) COP_{max} (b) COP_{static} (c) COP_{temp}

Fig. 3. ***Solar PV sizing for small, medium and large homes when sizing based on annual solar energy generation (red slashed bars) and winter solar energy generation (crossed slashed bars) under all the different coefficient of performance (COP) models.***

of 10.632 MWh [20]; an expected outcome for a city with majority of the population belonging to low-income groups. Similarly, Figure 1b shows the existing peak demand on the electric grid with an average peak of 7.2 kW across all the homes. The maximum peak demand across all the homes is 10.5 kW. This analysis will allow us to understand how much the existing demand on the electric grid is and how much the additional demand from electric heat pumps demand will burden the electric grid.

(2) ***How much additional annual electric demand is added by the electric heat pumps?*** To quantify the annual electric demand from heat pumps, we sum the entire heating demand for each home and convert it to electricity using the conversion factors mentioned above. Figure 2a shows the probability distribution of additional electric demand from the heat pump transition for all COP models. With the COP_{max} model, just 27% of buildings observe more than 600 kWh increases in electricity demand. However, this demand increases drastically with the COP_{static} and COP_{temp} models, which show that 56% and 72% of buildings respectively experience more than 600kWh increases in electricity demand. As discussed above, the estimated increase in annual demand is helpful for the long-term capacity planning of the grid.

(3) ***How much additional peak electric demand is added by the electric heat pumps?*** The near-term impact of the transition to electric heat pumps is due to the additional peak demand added to the electric grid. Figure 2b shows the cumulative probability of added peak demands across all the homes for all COP models. Our analysis shows that the added peak demand for the median buildings in the COP_{max}, COP_{static} and COP_{temp} models are ∼0.54 kW, ∼0.75 kW and ∼1.84 kW respectively. This represents a significant increase in the peak electricity demand that can easily trigger upgrades for building-level meters, cables, and additional upgrades upstream including transformers.

(4) ***What is the increase in the net electric peak demand?*** Our analysis of peak demand from heat pumps paints an optimistic picture – for all COP models, the peak demand is 11KW for the high demand homes, which is very close to the existing peak demand. A small solar PV system can completely eliminate this added demand, but only with the addition of storage as heating demand peaks often occur at night. However, if we are to just eliminate the short-term impact on the grid, we can use solar and storage to remove the increase of the peak in the net demand, i.e., the original demand plus heat pump demand. To facilitate sizing for such a scenario, we also look at the increase in the net-peak demand. Figure 2c shows the net-peak demand. We observe that the net increase in the peak electric demand is much smaller than the peak heating demand and thus would require much smaller solar PV and storage.

Key takeaways. *For all COP models, the heat pump demand can significantly increase the annual electric demand, by up to 15%. The peak electric demand of heat pumps can be as high as 33% of existing peak, but it only increases the net peak demand by less than 5% due to statistical multiplexing.*

IV. Deep Decarbonization

In this section, we present an analysis of using solar photovoltaic (PV) systems and storage for deep decarbonization. In doing so, we answer the following questions.

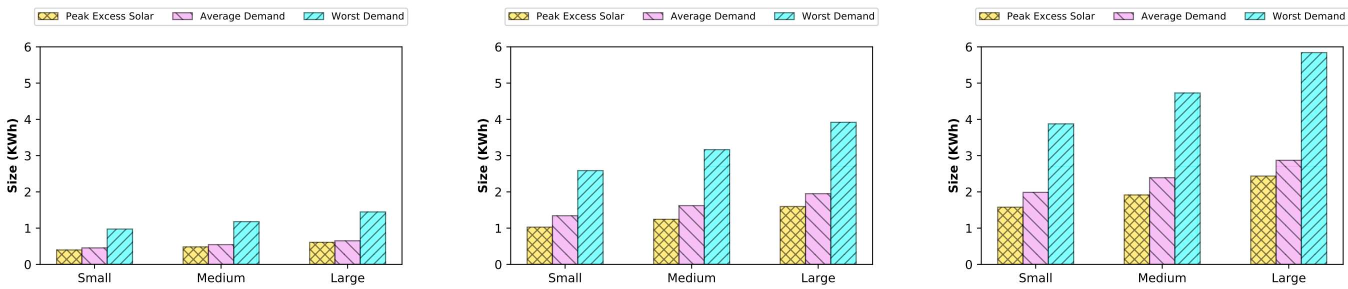
1) What are the different solar and storage sizing strategies to deeply decarbonize electric heat pumps?
2) What is the relationship between the cost of various sizing strategies and the carbon emission reductions?

We use a two step approach towards sizing; we first size the solar panel based on various sizing strategies and then size an appropriate battery storage based on one of the solar sizes. We present the solar panel and battery sizings by home size, where "small" homes are within the 25th percentile of home sizes, "medium" homes are between the 25th and 75th percentiles, and "large" homes are at the 75th percentile or larger.

A. Solar PV Sizing

Ideally, the power generation from solar panels should completely offset the additional electricity demand at each time instance of the year. However, since there is significant heating demand at night, even a solar panel of infinite size cannot meet the nighttime heating demand. Thus, we aim to produce as much solar power as possible given that no power can be generated during the night.

One approach to sizing solar PV systems could aim to offset the annual additional demand (*Annual Solar Sizing*). In this case, the power generation from solar panels will offset an electric heat pump's demand over one year time period. However, since solar power generation in the winter is often less than the rest of the year, the power demand in winter



(a) COP_{max} (b) COP_{static} (c) COP_{temp}

Fig. 4. ***Battery storage sizing for small, medium and large size homes with heat pumps operating under the maximum, static and temperature-aware COP models. Our three storage sizing strategies size the battery based on the excess solar, average heating demand, and worst night heating demand.***

may still be unfulfilled. In an effort to approach instantaneous matching of demand, we also size the solar panels based on the total winter heating demand (*Winter Solar Sizing*), which is the total heating demand for the entire winter season. In both methods, we generate a solar power generation trace for a 1kW array for a typical year using a publicly available solar modeling toolkit, such as Solar-TK [21]. We then scale the solar panel trace such that the energy generation from solar power matches the electricity demand of heating.

Figure 3 shows the solar PV size for small, medium, and large homes based on the annual heating demand and winter heating demand for all COP models. We observe that only a small solar panels of less than 1kW are needed to offset the heating demand on an annual basis for all COP models, while a larger solar panel of up to 0.6KW-2.5kW is needed to match demand during the winter season.

Key takeaway: *With the Annual Solar Sizing strategy, a solar panel of just 0.7kW is needed to offset the heating demand on annual basis for the largest home using the least efficient heat pump. However, with the Winter Solar Sizing strategy, the solar panel size increases by 4× for the largest home using the least efficient heat pump.*

B. Battery Storage Sizing

The battery storage is deployed to store the solar energy during the day and use it to fulfill heating load at night. The heating load, and the storage needed, differs across nights and owners may decide to operate their deployed solar plus storage in unique ways. In this section, we present three potential strategies of using solar plus storage that influence the size of battery storage. To keep this analysis contained, we use a single solar panel size that is based on the Winter Solar Sizing policy mentioned previously and present our results for different strategies for all COP models in Figure 4.

(1) ***Satisfying average night heating demand (Average Night Battery Sizing).*** In this strategy, the policy is to satisfy the average nighttime heating demand during winter. Since there is no solar generation at night, the heating demand needs to be met from battery storage. To size battery storage, we compute the average nighttime electric demand of heat pumps. We use this value as the size of the battery. The battery size required varies widely across COP models, with battery sizes ranging 0.45kWh-1.9kWh for small size homes throughout and 1.44kWh - 2.9kWh for large-sized homes. We note that this size will work on an average night, but may not work on all nights that have higher heating demand.

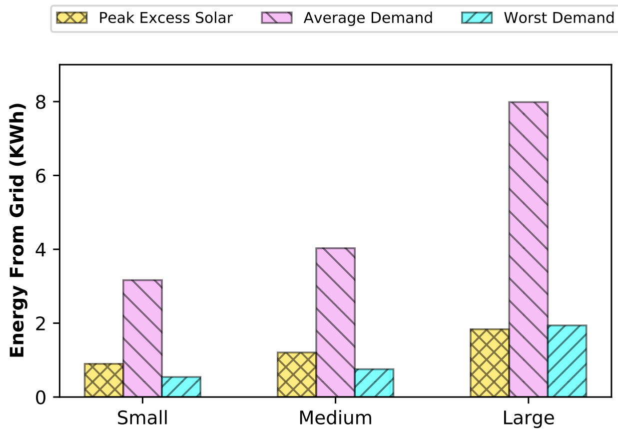
(2) ***Satisfying worst night heating demand (Worst Night Battery Sizing).*** In this strategy, the policy is to satisfy the nighttime heating demand of the worst night of the winter — the night with the highest heating demand. Instead of getting the average heating demand, we pick the maximum heating load to determine the size of the battery. This results in a battery size ranging from 0.9kWh-3.9kWh for small homes and 1.4kWh to 5.8kWh for large homes. This size is significantly higher than the Average Night Battery Sizing by a factor of 2× to 3×. However, this size will ensure that all the heating demand during all the nights is fulfilled with the battery. The benefits of a larger battery may be marginal since the nights with very high demand may be few in the winter.

(3) ***Storing peak excess solar energy (Excess Solar Battery Sizing).*** The previous sizing strategies assume that solar panels can produce enough energy to meet the average and worst night electric heating demand. However, if we keep the size of the solar panel fixed, we can only save excess energy that is left after meeting the heating load during the day. To analyze this scenario, we compute the daily excess solar energy. We use the peak daily excess energy as the size for the battery. This strategy provides a size that is lower than both the Average Night Battery Sizing and Worst Night Battery Sizing. This means that our solar panel size may not be enough to meet the worst case nightly demand or average nightly demand.

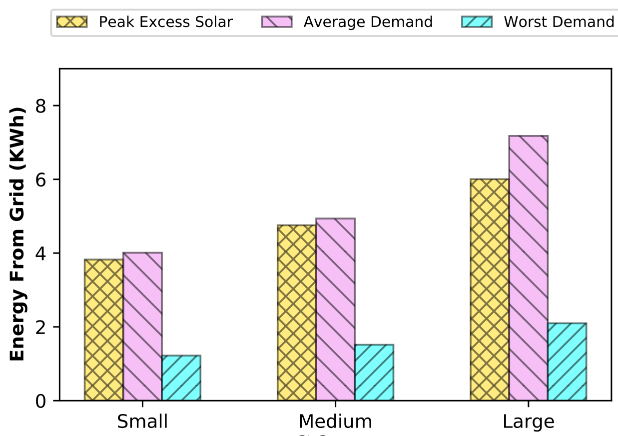
Key takeaway: *Under a realistic efficiency scenario, battery size ranges from 1.7kWh to 2.1kWh for small and large homes respectively when sized under the Excess Solar Battery Sizing policy. However, the battery size under the Average Night Battery Sizing policy is just 10% higher. This means that a solar panel sized based on the Winter Solar Sizing policy, along with a battery based on the Average Night Sizing policy could fulfill the heating demand entirely.*

C. Cost and Emissions Analysis.

We look at the cost and the carbon reductions under different sizing strategies. The final cost of installation for solar panels and storage depends on the incentives offered by utilities, state governments, and the federal government. We use the cost of



(a) COP_{static}



(b) COP_{temp}

Fig. 5. ***Electricity drawn from the grid using heat pumps with static and temperature-adjusted COP with various battery sizes.***

solar panels and battery storage after federal and state tax credits for the state of Massachusetts in the northeast United States, where the costs of solar PV and battery storage are \$2002 per kW [22] and \$1047 per kWh [23] respectively. We also report the carbon reduction under each solar plus storage combination. The annual net carbon emissions are zero since solar power produces equal or more energy. However, we use a stringent definition where we count emissions when either solar or battery cannot meet the heating demand, compared to emissions when heat pumps are grid-powered.

To explore the carbon emission reductions of various sizing strategies and COP models, we conducted a simulation to calculate the total electricity that would be drawn from the grid given our sizing strategies. We used a battery model with capacities shown in Figure 4 and Winter Solar Sizings shown in Figure 3. We found that under all sizing strategies and COP models, electricity drawn from the grid was minimal. In the worst case, the average home drew ∼8KWh from the grid during the year. This is less than 0.8% of the annual additional demand from the heat pump, as shown in Figure 5.

Table I presents the cost of solar panels, cost of different battery sizing options using the COP_{temp} model, and the carbon emissions under each configuration. All battery sizes

TABLE I
Cost and emissions of solar PV and solar PV + battery sizing strategies.

Sizing Strategy	**Small**	**Medium**	**Large**	**All**	**Emission Reduction (%)**
Annual Solar	\$1116	\$1350	\$1616	\$1360	58%
Winter Solar)	\$3467	\$4252	\$5144	\$4288	84.5%
Avg. Night Battery)	\$2079	\$2504	\$3005	\$2529	96.7%
Worst Night Battery	\$4059	\$4950	\$6117	\$5042	98.5%
Excess Solar Battery	\$1651	\$2004	\$ 2551	\$2069	97%

use Winter Solar Sizes. The most cost-effective option is storage-less Annual Solar or Winter Solar sized panels, both give us 58% reductions in carbon emissions. As we use Winter Solar Sizing and Average Night Battery Sizing, the energy from the grid accounts for just 3.29% of the total heating demand. However, any further increase in the storage size provides marginal reduction in emissions. As we quantify the gains using emissions reduced per dollar spent, an effort to reduce the total carbon footprint by using a bigger solar panel and a battery becomes very expensive.

Key takeaways. *The deep decarbonization of electric heat pumps on an annual basis can be achieved in a cost-effective manner using solar panels without storage. It also provides 58% reductions in emissions on hourly basis. The remaining 40.5% of possible reductions in emissions require storage and can cost an additional 3.7× to completely decarbonize.*

V. Related Work

There has been significant recent work on decarbonizing residential heating using air-source heat pumps [6], [7], [10]–[13]. However, this work focuses on transitioning heating to grid power, which does not completely eliminate the carbon emissions of heating. Another body of work investigates the feasibility of solar-air-source heat pumps [24]–[26], a configuration that may not be feasible for all buildings. There is also related work on evaluating the feasibility of solar PV and heat pumps in Austria [27]. However, this study focuses only on a small set of multi-family houses and ignores the potential of storage to deeply decarbonize the electric heating demand. Our work instead focuses on a large number of different types of homes, analyzes the impact of their transition to heat pumps on the electric grid, and considers both solar and storage.

VI. Conclusions

In this paper, we investigate the problem of sizing solar panels and storage to completely offset the added electricity demand of electric heat pumps, with the aim of providing low-cost solutions for deep decarbonization of residential homes. Our analysis shows that our solutions are low-cost and highly effective at reducing carbon emissions, with a minimum of a 58% reduction in carbon emissions per home. We also found that while it is possible to completely eliminate the carbon emissions of electric heating in homes, the cost of doing so drastically increases, and the marginal decrease in emissions may not be worth the price under all scenarios.

Acknowledgements. We thank the reviewers for their comments. This research was supported in part by NSF grants 2020888, 2021693, 2105494, 2136199, and 2136199.

REFERENCES

[1] "Massachusetts Household Heating Costs," https://www.mass.gov/info-details/massachusetts-household-heating-costs, 2022, (Accessed on 02/06/2023).

[2] S. Yanatma, "Europe's Energy Crisis in Data: Energy Costs Are More Than Double for Old Homes," https://www.euronews.com/green/2022/12/09/europes-energy-crisis-in-data-which-countries-have-the-best-and-worst-insulated-homes, 2022, (Accessed on 02/06/2023).

[3] IEA, "Heating," https://www.iea.org/reports/heating, 2022, (Accessed on 02/06/2023).

[4] "Massachusetts Department of Energy Resources - Massachusetts Household Heating Costs," https://www.mass.gov/info-details/massachusetts-household-heating-costs, Accessed June 2023.

[5] S. Nalley and A. LaRose, "Annual Energy Outlook 2022 (AEO2022)," 2022.

[6] J. Wamburu, N. Bashir, D. Irwin, and P. Shenoy, "Data-Driven Decarbonization of Residential Heating Systems," in *Proceedings of the 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation (BuildSys)*. ACM, 2022, p. 49–58. [Online]. Available: https://doi.org/10.1145/3563357.3564058

[7] A. Lechowicz, N. Bashir, J. Wamburu, M. Hajiesmaili, and P. J. Shenoy, "Equitable Network-Aware Decarbonization of Residential Heating at City Scale," in *ACM International Conference on Future Energy Systems (e-Energy),*. ACM, 2023, pp. 268–272. [Online]. Available: https://doi.org/10.1145/3575813.3576870

[8] A. M. Brockway and P. Delforge, "Emissions Reduction Potential from Electric Heat Pumps in California Homes," *The Electricity Journal*, 2018.

[9] H. Zhang, L. Zhou, X. Huang, and X. Zhang, "Decarbonizing a Large City's Heating System Using Heat Pumps: A Case Study of Beijing," *Energy*, 2019.

[10] A. Hopkins, K. Takahashi, D. Glick, and M. Whited, "Decarbonization of Heating Energy Use in California Buildings," *Synapse Energy Economics*, 2018.

[11] S. Billimoria, L. Guccione, M. Henchen, and L. Louis-Prescott, "The Economics of Electrifying Buildings: How Electric Space and Water Heating Supports Decarbonization of Residential Buildings," in *World Scientific Encyclopedia of Climate Change: Case Studies of Climate Risk, Action, and Opportunity Volume 3*. World Scientific, 2021.

[12] N. Kaufman, D. Sandalow, C. R. Di Schio, and J. Higdon, "Decarbonizing Space Heating with Air Source Heat Pumps," *Center Glob. Energy Policy*, 2019.

[13] J. Wamburu, E. Grazier, D. Irwin, C. Crago, and P. Shenoy, "Data-driven Decarbonization of Residential Heating Systems: An Equity Perspective," in *ACM International Conference on Future Energy Systems*, 2022.

[14] "Air-Source Heat Pumps — Department of Energy," https://www.energy.gov/energysaver/air-source-heat-pumps, 2022, (Accessed on 09/07/2022).

[15] J. Winkler, "Laboratory Test Report for Fujitsu 12RLS and Mitsubishi FE12NA Mini-split Heat Pumps," National Renewable Energy Laboratory (NREL), Tech. Rep., 2011.

[16] K. Neumeister, "2022 Solar Incentives and Rebates (Top 10 Ranked States)," https://www.ecowatch.com/solar/incentives, 2022, (Accessed on 09/08/2022).

[17] U. EIA, "Battery Storage in the United States: An Update on Market Trends," *US Energy Information Administration (EIA)*, 2020.

[18] "How to calculate heat pump cop - nordic heat pumps," Maritime Geothermal, 08 2015. [Online]. Available: https://www.nordicghp.com/2015/08/how-to-calculate-coefficient-of-performance/

[19] G. Schivley, I. Azevedo, and C. Samaras, "Assessing the Evolution of Power Sector Carbon Intensity in the United States," *Environmental Research Letters*, vol. 13, no. 064018, June 2018.

[20] "Residential Energy Consumption Survey (RECS)," https://www.eia.gov/consumption/residential/data/2020/, 2020.

[21] N. Bashir, D. Chen, D. Irwin, and P. Shenoy, "Solar-tk: A data-driven toolkit for solar pv performance modeling and forecasting," in *2019 IEEE 16th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*, 2019, pp. 456–466.

[22] "How Much Do Solar Panels Cost in 2023?" https://www.energysage.com/local-data/solar-panel-cost/, 2023, (Accessed on 02/07/2023).

[23] "How Much Do Storage Systems Cost In Massachusetts in 2023?" https://www.energysage.com/local-data/energy-storage-cost/ma/, 2023, (Accessed on 02/07/2023).

[24] Y. Liu, J. Ma, G. Zhou, C. Zhang, and W. Wan, "Performance of a solar air composite heat source heat pump system," *Renewable Energy*, vol. 87, pp. 1053–1058, 2016, sustainable energy utilization in cold climate zone (Part II). [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148115302810

[25] S. Ran, W. Lyu, X. Li, W. Xu, and B. Wang, "A solar-air source heat pump with thermosiphon to efficiently utilize solar energy," *Journal of Building Engineering*, vol. 31, p. 101330, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352710219321369

[26] J. Long, K. Xia, H. Zhong, H. Lu, and Y. A, "Study on energy-saving operation of a combined heating system of solar hot water and air source heat pump," *Energy Conversion and Management*, vol. 229, p. 113624, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890420311511

[27] T. Schreurs, H. Madani, A. Zottl, N. Sommerfeldt, and G. Zucker, "Techno-economic analysis of combined heat pump and solar pv system for multi-family houses: An austrian case study," *Energy Strategy Reviews*, vol. 36, p. 100666, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2211467X21000523